Analysis of Indirect Solar Dryers Using Computational Fluid Dynamics – A Review

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Abstract* - Open sun drying methods and direct solar dryers suffer from a major setback of direct exposure to solar radiation. This makes the drying product susceptible to excessive moisture removal, loss of vital ingredients due photo degradation and contamination due to atmospheric pollutants. To mitigate these shortcomings, Indirect Solar Dryers are used. In indirect solar dryers, solar radiation is used to heat up the air in a solar collector. This heated air is then fed to the drying chamber where the material to be dried is present. Factors like mass flow rate of incoming air, temperature inside solar collector, temperature inside drying chamber, etc. affect the performance and efficiency of solar dryer which are studied using CFD. This study initially presents an outline of the solar radiation and its trends of utilisation as an energy resource. After that, an introduction Computational Fluid Dynamics (CFD) has been given which is used to validate the designs. Since the CFD analysis provides a competent simulation of actual phenomenon, it is being preferred over the experiments to reduce project costs.

Keywords : Computational Fluid Dynamics, Types of Solar Dryer, Solar Collector, Air Flow Simulation.

I. INTRODUCTION

1. Solar Radiation

As measured by NASA (USA), Earth being at a distance of 149.6 million km from the Sun, receives about 1368 Wm^{-2} of solar radiation. This amount of solar energy is known as Total Solar Irradiance (TSI). However, only 70% of TSI is absorbed by Earth. Remaining 30% is reflected back to space. Solar radiation reaching the Earth's atmosphere mainly consists of three major types of electromagnetic (EM) waves.

1) Infrared (IR) waves($\lambda > 0.8$ μm)

2) Visible light waves(0.4 μm $< \lambda <$ 0.8 μm)

3) Ultraviolet (UV) waves ($\lambda <$0.4 μm)

Out of these three waves, infrared rays are prominently responsible for gradual increase in the temperature of the Earth. As solar radiation enters the Earth's atmosphere, a part of it is absorbed by atmosphere, lithosphere and hydrosphere. Rest of the energy is reflected back in the form of low-energy infrared radiation (IR). Since most of this reflected IR radiation is reabsorbed by the pollutants and carbon-dioxide, it contributes in maintaining the temperature of Earth. Thermal energy stored in the IR radiation is put to use in a similar way in solar dryers to dry various produce like foods and industrial raw materials.

2. Need Of Solar Energy As A Renewable Resource

Solar energy is one the most abundant renewable energy source available to mankind. As per the Renewables Global Status Report - 2016 by REN21 [1], 19.2% of global final energy consumption for the year of 2014 was contributed by renewable energy resources including solar power. Solar power production in 2015 was nearly 10 times its production in 2005. Renewable Energy Highlights published by International Renewable Energy Agency on July 1, 2016 [2]showed that the global solar power generation saw an increase of 39% for the year 2013-2014. It was the highest growth rate seen for any renewable energy source during the same duration. However, such a positive trend of shift towards solar energy utilisation came at a cost.

Much of Earth's temperature rise in the past century is mainly attributed to industrial revolution. Rapid usage of fossil fuels, increased dependence on mechanised products, improved manufacturing techniques, consumerism, gasoline powered automobiles and several innumerable factors led to increased emissions of carbon-dioxide. Since carbon-dioxide is one the major absorbers of low-energy IR radiation, the need to reduce the carbon emission has been a debatable topic for world leaders since 1930s when this issue was brought to light by Gay Stewart Calendar. Calendar made use of Arrhenius's calculations to draw a relation between global temperature rise and carbon-dioxide emissions [3]. He showed that between 1880 and late 1930s, there was an increase of 0.3ºC in the global temperature of Earth's lithosphere. His results were soon validated in a research study by Hawkins et al. [4].

Effect of these anthropogenic activities was supported by a study done by Shafiee et. al. [5]. It stipulatedthat our oil, coal and gas reserves will last approximately 35, 107 and 37 years respectively.With time extrapolation, world can depend on coal up to year 2112, gas beingthe second last fossil fuel available till 2042. Even on the availability of such numbers forcingthe world to search for alternate renewable energy sources, statistics representing the current rate of investment in fossil fuels doesn't seem to dwindle.

Survey done by Arbuthnott et al. [6]shows that huge monetary and managerial investment done in fossil fuel and large profitsearned by their trading pose a threat to the future investment in renewable energyresources. This reluctance of monetary investment for future betterment at the cost of currentinvestments is called escalation of commitment or sunk cost fallacy. Michael et al. [7] deduceda similar fate of investment in industrialised colonies. Thus, need of the hour is to shift the ideology ofenergy consumption from non-renewable to renewable energy resources. Carbon emissions need to be reduced and focus must be on long-term sustenance of human race on earth rather than short-term monetary profits.

Lazkano et al. [8] suggested one such way to ease the shift from non-renewable to renewable energy consumption. By focusing on the development of efficient electricity storage mediums, carbon emissions can be curbed. This rationale would also increase the efficiency of present fossil-fuels technologies and promote the use of renewable electricity.

Zou et al. [9] forecasted the energy trends of 21st century based on the past trends of oil, coal, natural gas, and innovations in renewable energy resources. Study predicted that the share of renewable energy resources is expected to reach 20% of primary energy consumption by 2030 and great strides in energy consumption can be achieved if efficient and innovative energy storage mediums are developed. Since coal industry will transit from high-carbon coal to low-carbon coal, reduced carbonemissions and pollutants from industries will yield less carbon-footprints.

However, this transition to non-renewable energy resources suffers from technical, sociological and cultural implications. In a study by Jarvensivu [10], effects of dependence on renewable energy resources alone were documented. Mustarinda, an international artistic cum scientific residency was put to use to examine the human behaviour and its adaptability to the usage of renewable resources alone. Both inspiring and life-threatening effects were discovered with this transition. Hence, lawmakers and stake-holders need to draft policies keeping in mind sound sustenance of human kind without affecting its present state of living. Since, adaptation of human kind to non-renewable energy took its time, so will to renewable energy resources. Saliently devised policies need to be devised to implement the use of renewable energy sources like solar energy, hydropower energy, wind energy, geothermal energy, and many more.

In this paper, focus will be on the analysis of solar energy using CFD to dry various food products and agricultural produce. In solar dryers, thermal energy stored in the solar radiation is used to remove the moisture content from the food items. Be it be pickles, mangoes, chillies, textiles, dairy products, etc., each product has a drying requirement of its own. Keeping this fact under consideration, several designs of solar dryers had been proposed over time. Each of these design is based on one or more drying techniques – open sun drying, direct and indirect. To reduce the cost of experimentation and testing, these designs were simulated using computational fluid dynamics (CFD).

3. Solar Dryer

Solar dryer is a device which utilises the thermal energy of solar radiation to remove the moisture content from the food products and agricultural produce. Based upon the method of interaction of solar radiation with the drying product, solar dryers are classified into three types.

a) Open-sun type solar dryer

b) Direct solar dryer

c) Indirect solar dryer

3.1 Open Sun Type Solar Dryer

In open sun drying, a thin layer of material having high moisture content is laid out on a flat surface upon which ample sunlight falls throughout the day. Due to drift of wind flowing above the material and solar radiation heating up the material, moisture evaporates from the drying product. There is no control over the rate of removal from the drying product. Frequent manual checking is required to maintain the quality and moisture content in the produce. This method suffers from a major setback that many a times, material quality is deteriorated due to rain, excess heat and pollutants in the atmosphere. The open drying process is not suitable for large amounts of products processed by large firms. Apart from the disadvantages of high maintenance cost, large area requirement, and decreased quality of products, it also involves a labour-intensive process before the products can be ready for storage. This method is becoming obsolete due to advent of better solar drying methods.

3.2 Direct Solar Dryer

A direct solar dryer consists of a drying chamber in which the sun rays fall directly on the drying product. A transparent sheet of glass protects the drying produce from atmospheric phenomena like precipitation, smog, dust-storms, etc. In direct solar dryer, air can allowed to flow through the produce either due to natural convection or due to forced convection using blowers. Since sun rays fall directly on the produce and due to less air flow as compared to open-sun type dryer, the drying produce can deteriorate in quality quickly.

Gbaha et al. [11] designed a natural convection direct solar dryer as shown in Fig. 3.1. The sunrays fall directly on the drying area while air due to natural convection, flows through the produce kept on the tray. Thermal energy of the solar radiation evaporates the moisture from the produce while air due to convection, removes this moisture from the drying chamber. The main focus of this paper was to study the relation between kinetics and the heat balances of drying process. Most of the material for construction of solar dryer was locally available.Major demerit of direct solar dryer is that there is no control over the rate of the drying product and amount of solar radiation falling on the produce which severely affects the quality of drying produce.

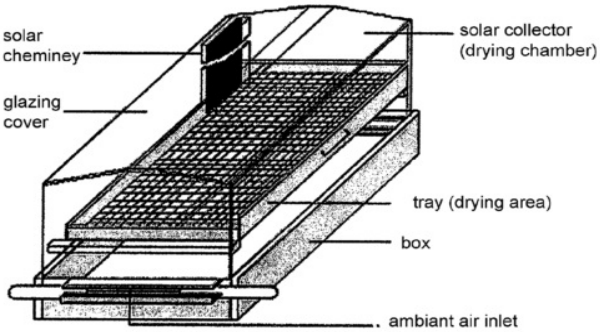


Fig. 3.1 : Natural convection direct solar drier [11]

Janjai et al. [12] discussed the disadvantages of direct solar dryer. Direct solar dryers are only suitable for small scale drying process due to which their commercialisation is limited. Due to entrapment of moisture in the drying chamber, condensation occurs on the transparent glass cover which can reduce the amount of solar radiation falling on the drying product. Only a part of energy stored in solar radiation is absorbed by the drying produce. Rest of the energy is used up in heating the air inside the drying chamber which results in low efficiency of direct solar dryer.

3.3 *Indirect Solar Dryer*

To overcome the shortcomings of open-sun type solar dryer and direct solar dryer, indirect solar dryer is used. In indirect solar dryer, a solar collector is used to heat air using the solar radiation. This heated air is then fed to the drying chamber where the product to be dried is placed on a wire-mesh to allow air flow through it. A blower is used to regulate the rate of air flow inside the solar collector. Thus, uniformly dried product is obtained with reasonable drying time. Several designs of indirect solar dryer had been proposed based on the drying requirements and quantity of the produce.

Preeti et al. [13] designed a natural convection type indirect solar dryer to dry ginger. Since it was a natural convection solar dryer to avoid any dependence of efficiency on electrical energy input, the drying rates were not suitably fit for commercial purpose. To improve the thermal storage capacity of the solar collector, paraffin wax used as thermal energy storage medium.

To improve the efficiency of the indirect solar dryer, Slimani et al. [14] proposed a design of hybrid photovoltaic/ thermal solar collector. This design was suitable for use in indirect solar dryer. As shown in Fig. 3.2, a double-pass channel for air was constructed which was separated by solar cells, sandwiched between an upper layer of glass and a lower layer of tedlar. A metal plate of aluminium is present at the bottom of the collector which absorbs the solar radiation and heats up the air. One major advantage of this design is that it uses a part of solar radiation is used in generating electricity to run the inlet blowers and a part to heat up the air drawn in by the blower. Hence, no external energy source is required to run the blower, making this collector self-sufficient in electrical energy. A layer of glaze was also provided at top to produce a greenhouse effect to increase of air inside the collector.

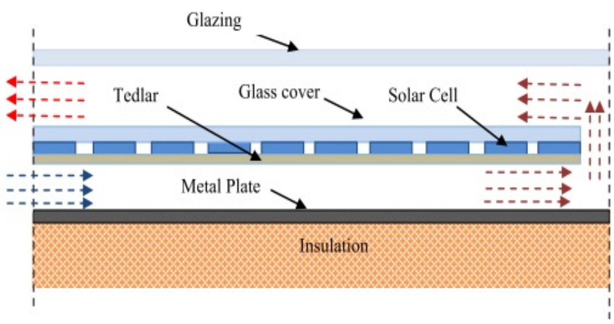


Fig. 3.2 : Hybrid PV/T solar collector [14]

Proposing a design of a solar dryer is not a big deal but analysing the proposed design using experimentation, simulation techniques, or both is a crucial step which has to be carried to validate the design. Since experimentation and testing of designs demand a separate financial budget, it becomes necessary to find alternate ways of validation. Moreover, designs once fabricated cannot be tampered with for modifications during testing to avoid random errors. Thus, numerical simulation techniques help to validate these designs. Basic physical equations concerning the phenomenon, numerical methods, computer programming and algorithms are used altogether to simulate the actual physical process with minimal error. Now, an introduction to CFD will be given followed by its use in the design and validation of solar dryers.

4. Computational Fluid Dynamics

Computational Fluid dynamics [15] is simulation technique which makes use of numerical methods, physics and computer resources to simulate physical phenomenon of fluid flow in computers. One major fact which supports the use of CFD is that it provides quite a correct simulation of fluid phenomena making it widely acceptable amongst the scientific and engineering community. CFD is governed by same laws as applied to classical mechanics of rigid bodies. However, the form in which they are used is different. Basically, a fluid flow phenomenon is governed by three modes of conservation of physical quantities, namely – mass, momentum, and energy. Equations of these three conservation phenomena are given below.

a) **Mass conservation:** Conservation of mass is governed by continuity equation given by (1)

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{V}) = 0 \qquad (1)$$

b) **Momentum conservation:** Mass conservation is governed by a partial differential equation which is a modified form of Newton's 2nd law of motion for fluids. This equation is called Navier-Stokes (NS) equation. In conservation form, complete NS equation for cartesian co-ordinates x, y, z respectively is given by (2), (3) and (4), provided the fluid is newtonian.

For x-direction,

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(\lambda\nabla.\mathbf{V} + 2\mu\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right] + \rho f_x \qquad (2)$$

For y-direction,

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial y}\left(\lambda\nabla.\mathbf{V} + 2\mu\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial x}\left[\mu\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left[\mu\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)\right] + \rho f_y \qquad (3)$$

For z-direction,

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial P}{\partial z} + \frac{\partial}{\partial z}\left(\lambda\nabla.V + 2\mu\frac{\partial w}{\partial z}\right) + \frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[\mu\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)\right] + \rho f_z \qquad (4)$$

c) **Energy conservation:** Energy conservation equation in case of fluid is a modified form of the first law of thermodynamics. Since an infinitesimal fluid element has internal energy e and kinetic energy $V^2/2$, the conservation form of energy equation is given by (5). Summation of e and $V^2/2$ makes up the total energy of the fluid element.

$$\frac{\partial}{\partial x}\left[\rho\left(e + \frac{V^2}{2}\right)\right] + \nabla.\left[\rho\left(e + \frac{V^2}{2}\right)\mathbf{V}\right] = \rho\dot{q} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) - \frac{\partial(uP)}{\partial x} - \frac{\partial(vP)}{\partial y} - \frac{\partial(wP)}{\partial z} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} - \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} + \rho\mathbf{f}.\mathbf{V} \qquad (5)$$

Along with the above three conservation phenomena, several other parameters like boundary conditions, algorithm used to couple equations (1)-(5), etc. are necessary to simulate the physical processes involving fluid flow. One can either write its own code to simulate the physical phenomenon or can use commercially available software packages. These software packages are either GUI based like Ansys, Star CCM+, Fluidyn MP, or command line based such OpenFOAM. In these softwares. CFD codes are structured around the numerical algorithm that can handle the fluid flow. The general procedure followed to solve a computational problem involves three steps:

a) **Pre-processing**: In this step, geometry, physical model of the problem, meshing and boundary conditions are defined.

b) **Solving**: In this step, discretized equations formed from the partial differential equations are solved through iterations.

c) **Post-processing**: In this visualization tools are used to analyze the problem in a best possible way. It includes contour representation, rendering, partical tracking etc. Variation of physical parameters of the fluid flow like temperature, pressure, vorticity, etc can be visualised.

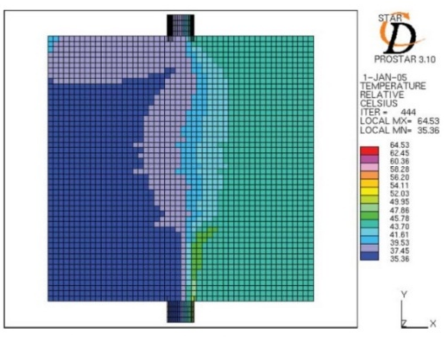
II. LITERATURE REVIEW

Currently, simulation techniques are most prevalent amongst the scientists and engineers owing to their increasing accuracy and stability, and cost effectiveness. In most industrial projects, multiple numerical simulations are performed on a product before the design is finalised and sent for fabrication. Similarly, current trends and advancements in CFD simulation has made it possible to rely on numerical results to design a product. In case of solar dryers, it helps to analyse the flow of air inside the drying chamber and to visualise the distribution of various parameters like temperature, velocity and pressure as per the requirement of drying product. Such a use of CFD has been discussed in the following cases to analyse and modify the existing or proposed design of solar dryer.

Ekechukwu et. al. [16] proposed as design of natural convection type indirect solar dryer as shown in Fig. 5.1 and analysed it using STAR – CD code which has an inbuilt pre-processor, and a post-processor named PROSTAR. The solar dryer consisted of a horizontal solar collector which was bent by 90° to connect it to the drying chamber. At the top of drying chamber, a 2 m long chimney was provided to enhance the stack effect. The analysis was done in both 2D and 3D; however 2D results were totally acceptable to reduce the computational cost. The drying product was modelled as a porous medium with moisture removal at its top surface. It was observed that the air velocity was higher near the centre than at the walls which lead to non-uniform drying. To remove this anomaly, a flow distribution mesh was introduced at 0.3 m from the floor. One major drawback of this study was that the temperature distribution was not symmetric in the drying chamber even after the introduction of baffles.

To aid the farmers of Nigeria in drying their agricultural produce without significant financial investment, Adeniyi et. al. [17] proposed a design of indirect solar dryer box based on the average solar radiation received in Akure City, Nigeria. Though open sun drying methods were prevalent in the region, they resulted in huge monetary losses as direct exposure to sunlight reduced the quality of drying produce. To analyse the solar box design, CFD simulation was done using Monte-Carlo ray tracing method. Experimental testing was also done to validate the simulation results. Major merit of this design was its low cost of fabrication. The glass cover used in the solar box was tilted at angle of 7º to the horizontal for maximum receptivity of solar flux. Experimental results deviated from the simulation in the initial hours of the days under observation. It was due to the constant ambient temperature assumed in the simulation.

Ingle et. al. [18] presented a design of solar collector using an absorber flat plate having wavy shape. A 4 mm thick glass plate was used to receive the solar radiation. The geometry for the CFD simulation was made in ANSYS Workbench. Its unstructured meshing having 15 million elements was done in ANSYS ICEM which helped in its simulation in ANSYS FLUENT. Steady state conditions were assumed and 3D segregated solver was used. K-ε viscous model was used for the simulation. No slip condition was considered at fluid (air)-solid interface. Due to non-uniform flow pattern of air inside collector, usage of baffles is recommended.



Mid-z-axis temperature scalar plot within the chamber.

Fig. 5.1 : Unsymmetric temperature profile of air flow in drying chamber [16]

Andrew et. al. [19] designed a solar dryer to aid the farmers of Malaysia in drying the pepper berries. Both natural convection and forced convection cases of air flow were simulated to choose the best method for drying process. Simulation was done in STAR-CD, a simulation software for CFD. Block meshing was utilised to discretise the model of the solar dryer. It was found that the natural convection mode provided better homogeneity of the air flow inside the dryer chamber as compared to the forced convection air flow.

Suhaimi et. al. [20] simulated a tray solar dryer for large scale drying in which products can be dried at different vertical heights. Finite volume method was used in ANSYS FLUENT 12.1 to simulate the 3D air flow inside the dryer. Tetrahedral cells were used for the unstructured meshing and steady state conditions were chosen. Though velocities over different plates very significantly, however their temperature profiles were quite similar with a 1.2º C temperature difference between the trays. Humidity analysis was not done. Major drawback of this design was the uneven drying of the products in the trays due to uneven air velocity over them. Periodic shuffling of products in different trays was proposed but it wouldmostly increase the time and cost of the drying process.

Andrew et al. [21] developed an indirect solar dryer with a biomass backup burner which was used to dry the pepper berries. Major outcome of this study was that it retained the constituents of the berries as per the standards set by the American Seed Trade Association. Aluminium was used as the absorber plate in the solar collector and a biomass burner heated this aluminium plate through conduction process. The simulation had its residuals achieve a constant value from the iteration number 1350. The experimental results well agreed with the simulation outcomes.

A CFD simulation done by Ashish et al. [22] on solar dryer to study the natural convection of air flow through it. ANSYS 14.5 was used for the study in which transient mode was chosen to relate with the varying temperature conditions throughout the day. The distance between the glaze and the absorber plate was kept at 140 mm. The study suggested to use aluminium absorber plate during the winter months in India. Wei et al. [23] used a porous absorber in the chimney of the solar dryer to study the effects of various inclinations of the absorber on the heat transfer rates. The study also included the effects of dryer height on the outlet velocity and temperature of the chimney. With increase in height, the exit air velocity increases and the temperature decreases due to less time for heat transfer between heated air and the drying produce.

Sonthawi et al. [24] validated the CFD analysis of biomass driven solar dryer done in ANSYS Fluent, with the experimental results. He used coefficient of determination and root mean square tests to compare the results. The study used built-in κ-ε turbulence model which proved to be accurate for this simulation. A drawback of using biomass burner was seen in the experiment as the chamber temperature surged high due to uncontrollable heat from the biomass. Similar effects were observed in the simulation as moisture transport phenomenon was neglected.

Ambesange et al. [25] analysed the air flow in 2D through a solar dryer duct using ANSYS Fluent 14.5. The collector consisted of two thin galvanized iron sheets – corrugated and plain. A tempered glass was used to produce the green house effect inside the collector. The trapezoid design of the dryer helped in achieving the high temperature inside the drying chamber. Romero et al. [26] validated the design of an indirect solar dryer (named Tikin-2) used for drying of vanilla using ANSYS Fluent's Solar Load Model. The collector was tilted an angle of 21º with the horizontal. Thermo-hygrometers were used to measure the relative humidity as well as the temperature. The simulated and measured temperatures inside the chamber deviated a lot due to the assumption of constant convection coefficient of heat transfer.

Marian et al. [27] studied the convective try type solar dryer for various air flow rates and temperature profiles using COMSOL Multiphysics CFD. The dryer was studied in three positions of the shutter – fully closed, partially closed and fully open. No experimentation was done to validate the results. Major reasons could be the high fabrication costs.

III. CONCLUSION

With the growing need of alternate sources of energy to replace the fossil fuels, solar energy acts as perfect energy source. Though the investments in fossil fuels is high making it difficult for stakeholders to look into other energy pools, the need to sustain human life on Earth in future cannot be ignored. One such use of solar energy is in the drying process wherein the thermal energy stored in solar radiation is used to remove the moisture from the produce. Many designs of solar dryers had been proposed and fabricated which were then experimentally tested for various parameters like velocity, temperature profile, humidity, etc. Such tests not only increased the project cost but delayed the commercial execution of solar dryers. In such cases, Computational Fluid Dynamics (CFD) proves to be an effective simulation technique to measure and analyse the behaviour of the fluid (air) in the solar dryer.It can be concluded from this review that factors like non-uniform distribution of air velocity, temperature, moisture content inside the solar dryer are some issues which need further improvement. Also, there is wide scope of innovation in design considerations like addition of baffles, use of thermal storage materials, etc. which can enhance the efficiency of solar dryers.

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